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Land use change and the carbon debt for sugarcane ethanol production in Brazil

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A R T I C L E I N F O

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A B S T R A C T

Farming sugarcane, as a renewable source of ethanol for use as a fuel, is a common practice in Brazilian agriculture. Despite being renewable, whether ethanol use actually reduces greenhouse gas (GHG) emissions depends on how the sugarcane is produced. Studies have shown that land use changes due to sugarcane farming are responsible for a substantial amount of the carbon emitted into the atmosphere, and may be equivalent to, or even greater than, the great "villains" of global warming–the fossil fuels. In the context of climate change, are there alternative land use changes that could create a lower overall carbon debt for ethanol and sugarcane production? In attempting to answer this question, this study aimed to: (i) map carbon stocks in the Brazilian biomes; (ii) quantify the carbon loss under different scenarios of land use changes for sugarcane-ethanol production; (iii) calculate the payback time for land conversion to sugarcane; and (iv) quantify the current areas of cultivated and degraded pasture by biome. The results show that the carbon debt from the deforestation of Brazilian biomes for ethanol production is equivalent to 608 Mg CO_2 ha^{-1} for the Amazon, 142 Mg CO_2 ha^{-1} for the Cerrado and 212 Mg CO_2 ha^{-1} for the Atlantic Forest with respective payback times of 62, 15 and 22 years. However, carbon emitted from the conversion of existing pasture land to sugarcane production rather than forest would be much smaller, with a shorter payback time. We conclude that pasturelands, especially those already degraded, would be the most suitable areas for land conversion to sugarcane production for ethanol. Pasture recovery would increase carbon stocks, reduce GHG emissions and reduce the negative direct and indirect land use changes associated with sugarcane expansion in Brazil.

1. Introduction

Brazil has been a world leader in the use of agriculture for ethanol production. Among the most common crops, sugarcane has emerged as an excellent source of ethanol. However, conversion of new lands for sugarcane production has been shown to create more carbon emissions than the use of biofuels saves (Fargione et al., 2008). In this study, we ask what alternative land use changes could create a lower overall carbon debt for ethanol and sugarcane production in Brazil? To address this question, we undertook four research steps, first to map carbon stocks in the Brazilian biomes; next to quantify the carbon loss under different scenarios of land use changes for sugarcane-ethanol production; third to calculate the payback time for land conversion to sugarcane; and finally to quantify and locate the current areas of cultivated and degraded pasture by biome that might be suitable for conversion to sugarcane-ethanol production.

There is increasing international concern about the world's over-dependence on the use of petroleum and its derivatives, oil's increasing scarcity, and about the climate changes associated with the increase of greenhouse gases (GHG) in the atmosphere. Consequently, the search for alternative sources of low-carbon energy has become a global priority, with the goal of limiting the negative effects of these gases on the environment. In this context, sugarcane-ethanol has been proposed as a potential solution to global energy shortages, oil dependency, and air pollution. Ethanol has the advantages of being both renewable, and a more efficient source of energy with lower-carbon emissions.

Fargione et al. (2008) note that among the agricultural sources for ethanol and biodiesel (palm, soybean, sugarcane, corn, prairie biomass), ethanol has the highest ratio between renewable energy production and fossil energy consumption, with a reduction in carbon dioxide emissions of 91% compared to gasoline, according to Goldemberg (2007), and 80% according to Embrapa (2009). This positive energy balance makes ethanol an attractive biofuel, both for the economy of fossil fuel consumption and as a mitigator of greenhouse gases in the atmosphere. However, despite being an energy source with low CO_2 emission, its efficiency in the carbon economy depends heavily on

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where and how sugarcane is produced.

In a global future scenario of much lower CO_2 from energy sources, Brazil stands out as having multiple physical characteristics that are highly favorable to the production of ethanol, with the capacity to meet both domestic and international demand for this type of fuel (OECD-FAO, 2010). Brazil in particular, has been a leader in extracting ethanol from sugarcane and converting it for use as a fuel in cars, trucks and other forms of transportation. According to OECD-FAO (2012), it is expected that Brazil will represent 28% of the global production of biofuels by 2021. However, while Brazil is attracting worldwide attention because of its potential for biofuel expansion (Barros, 2009; Alkimim et al., 2015), the country has also drawn concern due to the high deforestation rates associated with this expansion (Skole and Tucker, 1993; Morton et al., 2006).

Between 2000 and 2008, agricultural commodity prices were the major factor responsible for changes in Brazil's deforestation rates in the Amazon. The annual loss of land to deforestation went from 18,165 km^2 in 2001–27,772 km^2 in 2004. After reaching a peak in 2004, the annual deforestation rate began to decrease, but it was interrupted by another increase in 2008 (Barreto and Araújo, 2012). From 1990 and 2006, the deforestation in the Cerrado and Pantanal was mainly related to the expansion of pasture while the Atlantic Forest showed a combination of pasture, commercial cropland and tree crops (De Sy et al., 2015; Sparovek et al., 2009).

What is more concerning about these deforestation rates is the divergence in the context of global warming, considering that they delay the beneficial reductions of greenhouse gas resulting from the conversion to production of ethanol in Brazil. In addition, the deforested land eventually becomes underutilized. As reported by Barreto and Araújo (2012), 15% of the deforested area in 2008, nearly 11 million hectares, ended up being underutilized by agriculture.

Deforestation and conversion of lands for the expansion of agriculture has a negative effect on the environment, considering that forests and soil are a great reservoir of carbon stored in the terrestrial biosphere (Houghton, 2000; Ramankutty et al., 2007). According to Foley et al. (2011) and Davidson et al. (2012), such land conversion has been pointed out as the main cause of negative impacts on the soil, leading to the loss of biomass and organic matter, which in turn also contribute to the increase of GHG emissions. When sugarcane is produced on lands already occupied by other agricultural crops, it forces the expansion of agriculture into other areas, causing an increase in GHG emissions as a result of indirect land use changes (Gibbs et al., 2008; Searchinger et al., 2008; Romijn, 2011). So, losses of carbon from aboveground and belowground biomass, and from soil end up generating a net carbon debt during the conversion of land to biofuel production.

Studies of deforestation and the carbon debt of biofuels by Fargione et al. (2008) suggest that if sugarcane were produced by converting existing forest and shrublands, then producing and burning biofuels could actually emit more greenhouse gas than burning fossil fuels. This land use conversion would generate a carbon debt for a long period of time, and would raise doubt about the biofuels as a replacement for high-carbon energy sources. Can these differences be quantified, and what land use changes would lower the overall CO_2 emissions? Fargione et al. (2008) considered the issue for biofuels worldwide, but noted that for Brazil's wooded Cerrado, emissions of sugar cane were 165 Mg CO_2 ha^{-1} and 100% of the biomass created contributed to the carbon debt. Nevertheless, the 17 year timespan necessary to repay the carbon debt could be much reduced if, as was suggested for the US, abandoned or marginal cropland was converted.

Considering the low cattle occupancy rates in Brazil and the large herds, intensification of livestock production and the use of existing pasture lands, as opposed to the conversion of forest ecosystems, have been proposed as a strategy to avoid indirect land use changes and their related GHG emissions (Maia et al., 2009; Lapola et al., 2010). The conversion of pasture to sugarcane-based ethanol production offers many advantages regarding the carbon debt associated with direct and indirect land use changes. The use of these areas for agricultural expansion would reduce deforestation and the land use competition for production of food versus biofuels, which in turn would increase carbon stocks in the soil by removing CO_2 from the atmosphere, and sequestrating it into the biomass and soil. If only existing pastures were used for new ethanol production, they could function as an atmospheric carbon sink. Under such circumstances, the conversion of pastures–especially degraded pastures–to ethanol production could be considered as a viable strategy for Brazil to combat GHG emissions, since this practice would increase carbon stocks, and consequently mitigate the greenhouse effect.

It is ironic that the conversion of lands for biofuels production in Brazil can also represent a loss to the environment (Azadi et al., 2012). It is, therefore, necessary to identify and locate current and future land use changes and the associated carbon debt of future expansion of sugarcane-ethanol production in Brazil. Many studies include payback times for ethanol, mitigation potential for agriculture and livestock sectors, and greenhouse gas balance from cultivation and direct land use change of recently established sugarcane areas (Fargione et al., 2008; Searchinger et al., 2008; Cerri et al., 2010; Mello et al., 2014; De Oliveira Bordonal et al., 2015), however they lack detailed geographic data on the locations of the cultivated and degraded pasture lands that would be ideal for biofuel production. Therefore, in this study we sought to: (i) map the carbon stocks in the above and below ground biomass, and in the soils of the Brazilian biomes; (ii) quantify the carbon debt emitted as CO_2 by the biomass and soil due to land use changes in the 3 Brazilian biomes–Amazon, Cerrado (Savannah) and Mata Atlântica (Atlantic Forest) − that are the main regions of sugarcane-ethanol production in Brazil and also for cultivated and degraded pastures; (iii) calculate the time required for sugarcane-ethanol use to offset the carbon debt caused by the conversion of land for ethanol production in these zones; and (iv) quantify the cultivated and degraded pasturelands by biome to identify where land conversion would present a viable alternative for the further expansion of sugarcane-ethanol production in Brazil.

2. Material and methods

Estimations of carbon stocks, carbon debt and payback time followed two steps (Fig. 1). Step one was collecting spatial data on carbon stock in the above and belowground biomass and the soil and municipal data on land use. Step two consisted of a literature review on the percentage of carbon loss, carbon stock under pasture and annual carbon repayment rates. The results obtained through geospatial analysis were combined with data from the literature review, and estimates of carbon stocks, carbon debt and payback time were calculated. Maps were also created to show the carbon stocks in the Brazilian biomes and the spatial locations of cultivated and degraded pasturelands.

2.1. Carbon stock database formation and application of a geographic information system (GIS)

Public data about estimates of carbon stock in the above and belowground biomass and the soil were compiled. Geographical information on carbon stocks was normalized to create a database with best estimates of carbon stock in the 3 Brazilian biomes. The carbon stock data on above and belowground biomass were created by Ruesch and Gibbs (2008) as estimated for the IPCC GPG Tier-1, which was based on the methods and values of the aboveground biomass for each type of vegetation provided by the Intergovernmental Panel on Climate Change (IPCC). The belowground biomass data (t C ha^{-1}), as reported by these authors, were obtained using the ratio of root biomass and living matter aboveground including leaves, branches and trunks.

Carbon stock for each biome was extracted using the capabilities of ESRI's ArcGIS 10. Operations involving map algebra were necessary to

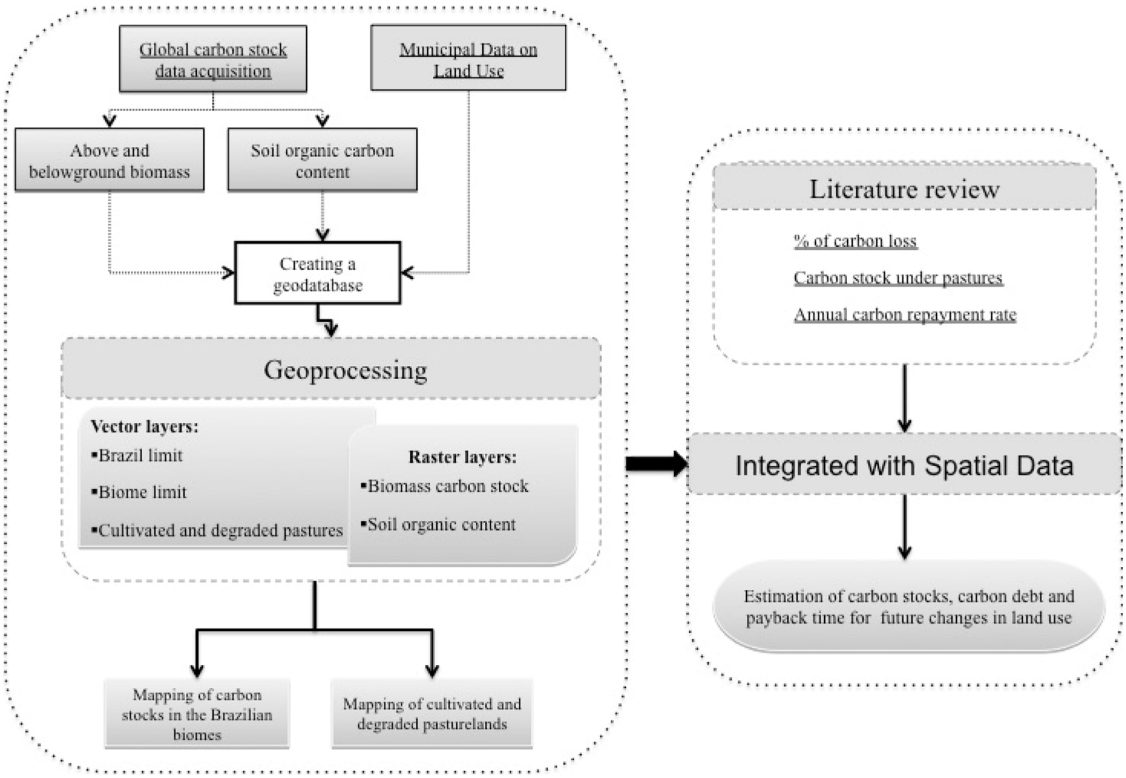


Fig. 1. Procedures followed to obtain the estimates of carbon stock, carbon debt and payback time for carbon emitted to the atmosphere due to land conversion.

combine carbon stock data in the above and belowground biomass and the soil to create a raster grid layer. The cells containing values of carbon in the above and belowground biomass were divided by 100, since the values were in units of 0.01 $t\,C\,ha^{-1}$. With both maps converted to the same map projection and to the WGS84 datum, arithmetic calculations were used to manipulate the geographic data by grid cell. The values obtained were used for mapping of carbon stocks in the above and belowground biomass in Brazil.

Global estimates of soil organic carbon stock (0–30 cm depth) in $t\,C\,ha^{-1}$ were added to the spatial database. The soil properties were stored in a table of typological units according to methods described in Hiederer and Köchy (2012). Carbon data for above and belowground biomass and soil had a global extent and spatial resolution of 1 km × 1 km. The zero value was considered as the absence of carbon values for a given area on both gridded maps.

The estimates of carbon stocks under pastures were obtained from a literature review, given that the spatial data acquired only provided values related to natural vegetation and soil, and not to pasturelands. Similarly, belowground biomass values were obtained. The amounts of cultivated and degraded pasture by municipality in Brazil (IBGE, 2016) was also included in the pastures database. They were joined to the geographic database via a common field (the municipality code) and the outline of the country and regions in ArcGIS 10 was used to create thematic maps.

Statistical values corresponding to the estimates of carbon stock were obtained in ArcGIS 10 and transferred to Microsoft Excel, where data were subjected to mathematical operations. To calculate the payback time caused by changes in land use, 9.8 $Mg\,CO_2\,ha^{-1}\,year^{-1}$ was used as a reference rate (Fargione et al., 2008), equivalent to the annual net compensation for ethanol production in relation to fossil fuels, which includes life cycle analysis of agricultural production, conversion to biofuel and combustion.

2.2. Estimates of carbon loss in forest biomass and soil

Total carbon stock was assessed using carbon loss percentage values in the soil and above and belowground biomass amounts associated with land use changes found in the literature. Estimates of carbon loss in the soil for the Amazon were 45.80% (Fargione et al., 2008) and the estimates for Cerrado were 15.21% (Fargione et al., 2008; Galdos et al., 2009; Mello et al., 2014). For the Atlantic Forest biome, due to the lack of more specific data in the literature, the carbon loss value was based on the conjecture that 25% of the carbon in the soil is lost in the conversion of a natural ecosystem when replaced by herbaceous crops (West et al., 2010). In addition, we assumed a loss of weight of the aboveground biomass for the Cerrado, Amazon and Atlantic forest of 9%, 9% and 14%, respectively, considering that these percentages would be equivalent to the amount of biomass used for the manufacturing of durable goods with a life cycle of more than 50 years, as considered by the IPCC (Fargione et al., 2008).

A literature review was also employed to obtain data on carbon percentage loss values from soils under pasture of 9.96% (Mello et al., 2014). With this information, the total carbon stock ($Mg\,C\,ha^{-1}$) was calculated, and converted to CO_2 values. Carbon dioxide values were calculated by multiplying the organic carbon by a conversion factor of 3.67 (Pearson et al., 2005) (Eq. (1)) to estimate the carbon loss (CO_2) emitted into the atmosphere due to land use change.

$$CO_2 = C \times 3.67 \quad (1)$$

Values of carbon stocks in forest ecosystems and pastures were calculated as the sum of the carbon stock in the above and belowground biomass and soil carbon loss minus forest products derived from deforestation. Three scenarios were created to identify the carbon debt associated with the conversion of land to sugarcane-ethanol production. In the first scenario, areas of native forest, such as Amazon, Cerrado and Atlantic Forest were converted to sugarcane. In the second scenario, sugarcane replaced areas of cultivated pastures, and in the third scenario, sugarcane substituted for degraded pasture lands.

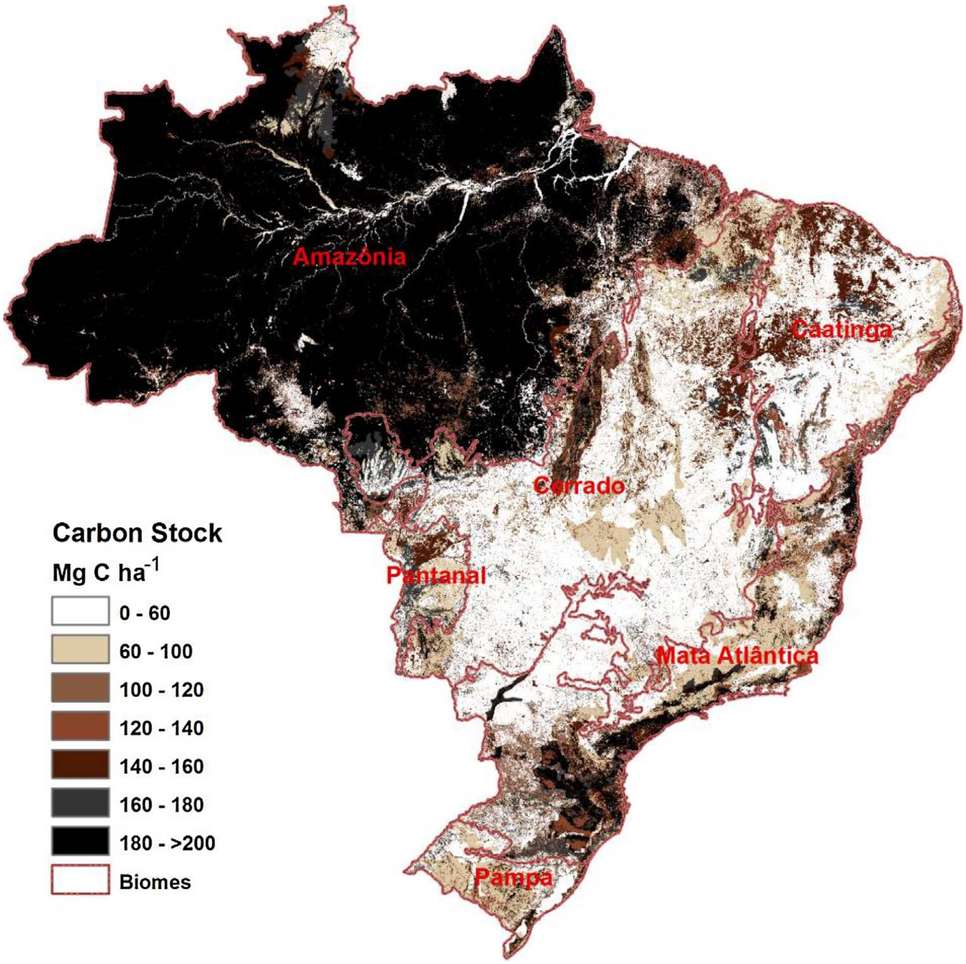


Fig. 2. Estimate of carbon stock in the above and belowground biomass and soil organic carbon for Brazilian biomes. Amazônia (Amazon), Mata Atlântica (Atlantic Forest), Cerrado (Savannah).

3. Results and discussion

3.1. Estimation of carbon stock in forest ecosystems and pastures

The highest carbon stocks in Brazil are located in the Amazon biome and in a few areas of the Brazilian coast under the influence of the Atlantic Forest biome (Fig. 2). From the quantitative data presented in Table 1, it was found that the carbon storage in the Amazon was approximately 69 billion tons of carbon in the above and belowground biomass, which is consistent with the value expressed by Carvalho et al. (2004). This number reaches over 90 billion tons when the amount of carbon in the soil is added. With regard to the Atlantic Forest, the percentage of carbon stored in the soil is greater than the values found for C of the above and belowground biomass, equivalent to 54%. The same can be observed for the Cerrado and Pampa biomes.

Areas covered by forests are an important source of carbon stocks, which once disturbed become large carbon sources, and play an important role in preventing global warming thanks to their carbon accumulation capacity both by the forests and soil (Bonan, 2008; Canadell and Raupach 2008; Keith et al., 2009; Pan et al., 2011). Protecting and expanding these forests is seen as a way of preventing GHG emissions. When these areas are cleared or replaced by shallow rooting systems, they lose their function as carbon storage and become one of the largest sources of greenhouse gas emissions from land use change. Carvalho et al. (2004) showed that deforestation in the Amazon is an example of this. According to Houghton et al. (2000), land use changes in this biome create a carbon deficit for Brazil of 150–250 million tons that are emitted annually, making it major contributor to GHG emissions.

Besides the forests, pasture has also received attention due to its potential to store more carbon. The recovery of degraded pastures to forest or agriculture has been identified as an alternative to the reduction of GHG emissions (Paustian et al., 1997; Conant and Paustian, 2002; Hutchinson et al., 2007; Christopher and Lal, 2007). This recovery increases carbon storage in the soils, which act as a carbon reservoir by removing carbon from the atmosphere and incorporating it, so potentially mitigating the greenhouse effect.

The carbon sequestration potential in pasture and the benefits of its recovery have also been the focus of attention among government GHG mitigation programs. The Brazilian government announced that the country would target a reduction in its GHG between 36.1 and 38.9% from projected 2020 levels (Cerri et al., 2010). A sectoral mitigation and adaptation plan to climate change has been proposed to consolidate an economy of low carbon emissions in Brazilian agriculture (ABC Plan – Low Carbon Agriculture Program). Among the programs launched by the Brazilian government, the recovery of degraded pastures has the greatest coverage area. With a commitment to recover an area of 15 million hectares of degraded pasture lands (Brazil Ministério do Meio Ambiente, 2015), the country would make more land available for food and biofuel production, preventing the deforestation of new areas for agriculture. Furthermore, such action would have a mitigation potential that is estimated to be 83–104 million megagrams of CO_2, which would be a significant contribution to the removal of carbon from the terrestrial atmosphere.

3.2. Sugarcane-ethanol production land use scenarios

Three land use change scenarios have been proposed to explore the carbon debt associated with the conversion of land to sugarcane-

Table 1
Carbon stock in the above and belowground biomass and soil organic carbon.

Biome		Area	Minimum Value	Maximum Value	Standard Deviation	Average Density	Storage
		(ha)	(Mg C ha^{-1})				(Mg C)
Amazon	a	418,244,300	0	193	59.31	165.69	69.3E9
	b		11	184	26.65	50.88	21.2E9
Total							90.5E9
Cerrado	a	203,937,200	0	193	49.55	36.36	7.4E9
	b		12	120	20.37	37.62	7.6E9
Total							15.0E9
Atlantic Forest	a	110,613,300	0	193	57.41	48.07	5.3E9
	b		12	159	28.79	55.68	6.1E9
Total							11.4E9
Caatinga	a	82,651,900	0	193	52.49	41.15	3.4E9
	b		13	74	11.28	28.00	2.3E9
Total							5.7E9
Pampa	a	17,776,400	0	193	40.76	30.30	538.5E6
	b		25	136	17.23	55.78	991.5E6
Total							1.5E9
Pantanal	a	15,131,300	0	128	51.34	66.75	1.0E9
	b		12	105	13.73	30.53	461.8E6
Total							1.4E9

a − estimates of carbon content in the above and belowground biomass.
b − estimates of carbon content in the soil.

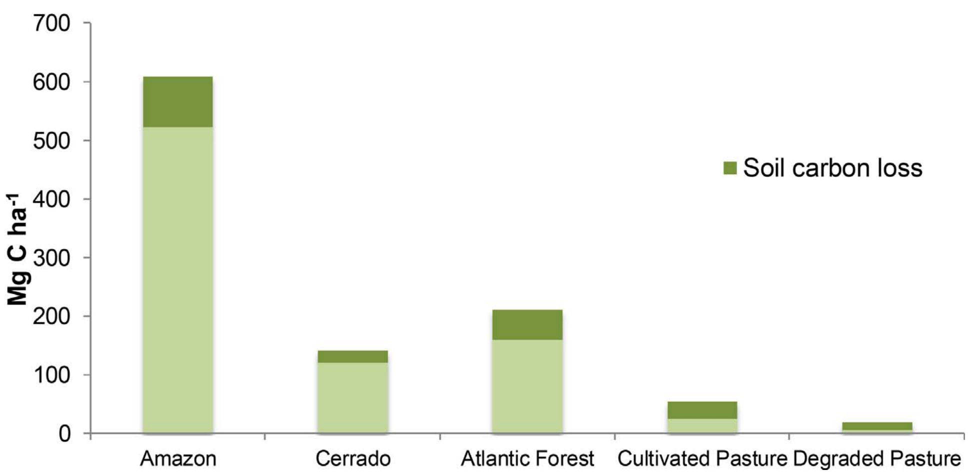


Fig. 3. Estimates of carbon stock in the Amazon, Cerrado and Atlantic Forest biome* and the cultivated and degraded pastures.
*Differently from estimates of carbon stock in those biomes, belowground data were already included in the soil data acquired from the literature for cultivated and degraded pastures

ethanol production. In the first scenario, the 3 Brazilian biomes are cleared and used for sugarcane production. In this case, the carbon debt would be 608.47 Mg CO_2 ha^{-1} in the Amazon, 142.43 Mg CO_2 ha^{-1} in the Cerrado and 211.63 Mg CO_2 ha^{-1} in the Atlantic Forest (Fig. 3 and Table 2). The loss of these forests, and their replacement by shallow rooting systems result in a loss of carbon accumulated in the tissues of trees in addition to a rapid loss of soil carbon due to the oxidation of organic matter, leading to greater release of CO_2 into the atmosphere (Nepstad et al., 1994). The carbon debt repayment (versus the benefits of ethanol use) related to this change in land use would be equivalent to 62 years in the Amazon, 15 years in the Cerrado and 22 years in the Atlantic Forest (Fig. 4).

In the second scenario, cultivated pastures are replaced with sugarcane production. This would represent a carbon debt of 55.34 Mg CO_2 ha^{-1} and require six years of biofuel use to repay. In the third scenario, the only degraded pasture land in the 3 biomes is converted to sugar cane, and the carbon debt is estimated to be 19.97 Mg CO_2 ha^{-1}. In this scenario, the environment could be compensated for that loss in just two years. The Carbon debt remains negative in all three scenarios of land use change for ethanol production, however carbon emissions would be much lower in the conversion of all forms of pasture to sugarcane, as well as the payback time. Reduced impacts in CO_2 emissions related to the conversion of pastures to ethanol production were also observed by Lapola et al. (2010).

A large amount of terrestrial carbon (CO_2) could be lost in the conversion of forest ecosystems to ethanol production. A large carbon debt associated with deforestation was also found by Silveira et al. (2000) and Fargione et al. (2008). However, if the conversion of pastures to ethanol production were to take place, these losses would be far less. Therefore, the carbon repayment period would be shorter, at approximately 2–6 years to pay off the carbon debt for this land conversion. This could be kept low by prioritizing degraded pasture land for sugarcane-ethanol production.

Despite its ability to store carbon during the production process, sugarcane-ethanol may be disadvantageous in the control of greenhouse gas emissions if it is produced in unchanged natural ecosystems. In these circumstances, the improved efficiency of ethanol in the carbon economy would turn out to be contradictory, given the impact of the deforestation that comes along with it. Once cleared, these areas would release large amounts of CO_2 into the atmosphere, and then the energy efficiency and low carbon energy secured by ethanol become questionable when compared to fossil fuels. Therefore, the expansion of

Table 2
Carbon debt caused by land use changes for sugarcane-ethanol production.

Quantity	Value	Unit	Estimates***	References
Amazon				
Above and below biomass	165.69	$Mg\,C\,ha^{-1}$		Ruesch and Gibbs (2008)
Forest product after 50 years*	23.20	$Mg\,C\,ha^{-1}$	14%	Fargione et al. (2008)
Soil carbon	50.88	$Mg\,C\,ha^{-1}$		Hiederer and Köchy (2012)
Soil carbon lost	23.30	$Mg\,C\,ha^{-1}$	45.8%	Fargione et al. (2008)
Carbon debt total**	165.79	$Mg\,C\,ha^{-1}$		
Carbon debt total	608.47	$Mg\,CO_2\,ha^{-1}$		
Cerrado				
Above and below biomass	36.36	$Mg\,C\,ha^{-1}$		Ruesch and Gibbs (2008)
Forest product after 50 years*	3.27	$Mg\,C\,ha^{-1}$	9%	Fargione et al. (2008)
Soil carbon	37.62	$Mg\,C\,ha^{-1}$		Hiederer and Köchy (2012)
Soil carbon lost	5.72	$Mg\,C\,ha^{-1}$	−7.8%; 0.2%; 6%; 8.4%; 5.1%; 15%; 80%; −0.7%; −9%; −0.6%; 51%; 9.3%; 30%; 26% (Avg = 15.21%)	Fargione et al. (2008); Galdos et al. (2009); Mello et al. (2014)
Carbon debt total**	38.81	$Mg\,C\,ha^{-1}$		
Carbon debt total	142.43	$Mg\,CO_2\,ha^{-1}$		
Bioma Mata Atlântica				
Above and below biomass	48.07	$Mg\,C\,ha^{-1}$		Ruesch and Gibbs (2008)
Forest product after 50 years*	4.33	$Mg\,C\,ha^{-1}$	9%	
Soil carbon	55.68	$Mg\,C\,ha^{-1}$		Hiederer and Köchy (2012)
Soil carbon lost	13.92	$Mg\,C\,ha^{-1}$	25%	West et al. (2010)
Carbon debt total**	57.66	$Mg\,C\,ha^{-1}$		
Carbon debt total	211.63	$Mg\,CO_2\,ha^{-1}$		
Cultivated Pasture				
Above biomass	6.89	$Mg\,C\,ha^{-1}$	8.66; 5.12	Szakács (2003)
Soil carbon	82.23	$Mg\,C\,ha^{-1}$	69.86; 94.60	D'Andréa et al. (2004); Rangel and Silva (2007)
Soil carbon lost	8.19	$Mg\,C\,ha^{-1}$	9.96%	Mello et al. (2014)
Carbon debt total**	15.08	$Mg\,C\,ha^{-1}$		
Carbon debt total	55.34	$Mg\,CO_2\,ha^{-1}$		
Degraded Pasture				
Above biomass	1.78	$Mg\,C\,ha^{-1}$	1.3; 2.25	Szakács (2003)
Soil carbon	36.80	$Mg\,C\,ha^{-1}$	32; 41.6	Szakács (2003)
Soil carbon lost	3.67	$Mg\,C\,ha^{-1}$	9.96%	Mello et al. (2014)
Carbon debt total**	5.45	$Mg\,C\,ha^{-1}$		
Carbon debt total	19.97	$Mg\,CO_2\,ha^{-1}$		

*Forest product after 50 years – Amount of biomass used for the manufacturing of durable goods with a life cycle of more than 50 years.
**Carbon debt total (Mg C ha-1) = Above and below biomass - Forest product after 50 years + Soil carbon loss.
***Estimates – Cultivated and degraded pasture: above biomass and soil carbon are in t C ha-1.

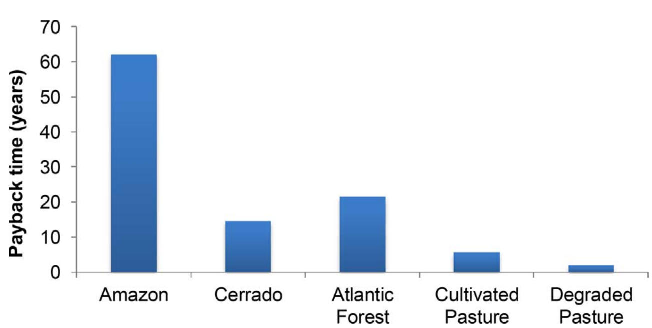


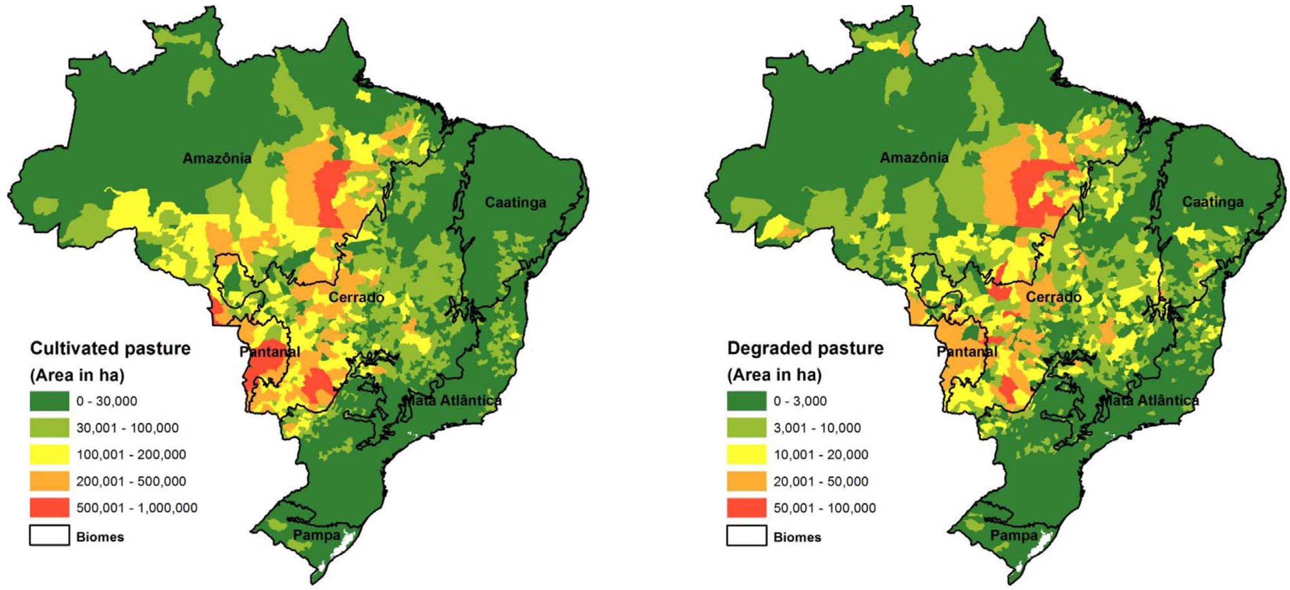
Fig. 4. Time (years) to repay the carbon debt due to the conversion of land to ethanol production*.
*Note that estimates of carbon payback time may vary depending on which mode of production and/or management system for ethanol production (burning the bagasse or not) has been implemented. Payback time for first generation ethanol would differ from that of cellulosic ethanol (second generation), which uses the bagasse to produce additional fuel instead of discarding or burning it.

sugarcane should be directed to pasture due to its short payback periods, and especially to degraded pastures.

3.3. Quantification of pasturelands in the Brazilian biomes

The Cerrado biome has the largest amount of degraded pasture, equivalent to 45% of the total, followed by the Amazon (25%) and the Atlantic Forest (18%) (Fig. 5). The total degraded pasture in the Brazilian biomes is almost the same as the total land covered by current sugarcane cultivation in Brazil, estimated at 9 million hectares (IBGE, 2012; INPE, 2012). The pasture use intensity associated with unsustainable management practices leads to soil depletion reflected by a sharp reduction in carbon stocks (Cerri et al., 2007). Thus, the conversion of degraded pastures to agricultural production has promise as a viable alternative, not only considering the expansion of sugarcane production in the country–since the areas where they operate are representative of biomes that were deforested–but also due to the increase in carbon stocks from their recovery.

Recovering degraded pastures could avoid other land use changes and spare forestlands. Even as short-term actions, the inclusion of these emissions in the national accounts is a key element to reducing domestic emissions of gases that cause the greenhouse effect. According to data made available by Conant et al. (2001) − that were obtained through surveys in 115 areas with 300 sampling points − the use of



Biomes	Degraded Pasture (ha)	Cultivated Pasture (ha)
Amazon	1,795,020	18,434,626
Cerrado	3,160,127	29,851,399
Atlantic Forest	1,268,827	13,222,382
Caatinga	837,466	3,612,435
Pampa	31,045	301,646
Pantanal	3,067	105,349

Fig. 5. Thematic map of cultivated and degraded pasture distribution in the Brazilian biomes.

pasture recovery practices significantly increased the carbon stocks in the soil in 74% of the surveyed areas.

Making more land available for converting pasturelands to sugarcane production, as suggested here, could be applied throughout Brazil as a way to expand low-carbon agriculture in the country. This would take the pressure off of Brazil's biomes, and increase ethanol production to meet both the domestic and international demand for biofuel. Thus, it is not necessary for Brazilian agriculture to rely on the conversion of new areas for ethanol production. According to the World Wildlife Fund (2009), the conversion of pasture areas for agriculture would be enough to make more land available for future usage that would consequently reduce deforestation rates over time in Brazil.

Goldemberg and Guardabassi (2009) considered the concerns regarding land use change for sugarcane production in Brazil to be somewhat exaggerated. As much as they seem to be exaggerated, these concerns cannot be considered independently of the country's current state. The real purpose of this question it is not merely to stereotype ethanol as good or bad in the history of direct and indirect land use changes, but to call attention to the negative effects with which this type of alternative energy is associated.

Expanded sugarcane-ethanol production would replace pasturelands, which, according to Amaral et al. (2008) and Adami et al. (2012), represent a total of almost 70% of the converted land areas. With a loss of space for livestock, indirect land use changes are triggered, perhaps leading to deforestation of new areas for pasture. As shown in this study, the degraded pasture area usable for ethanol production would double the area for sugarcane cultivation in Brazil. Pastureland conversion to sugarcane would not incur a major biofuel carbon debt as a result of land clearing for livestock production, as this could also use degraded pasture land.

The total area of pasture from IBGE was acquired from questionnaires answered by farmers, which means that these data may vary, and the amount of degraded pasture provided in the questionnaires may have been underestimated, since the area was not directly measured. Furthermore, the definition of degraded pasture by IBGE is not very specific. As pointed out by Braz et al. (2013), the classification of pastures, considering farmers' opinion, is not always accurate. Besides, census tracts do not cover the whole territory of Brazil. In addition, pasture data for Brazil are based on the agricultural census of 2006 (IBGE, 2016), which means that this database is already obsolete. Accordingly, a database with accurate and current information on the distribution of pastures in Brazil would be necessary for more timely information to be generated. Nevertheless, this is the only public agricultural database available in Brazil.

Estimates of carbon in the above and belowground biomass and soil also have limitations, especially with regard to their spatial scale. The working range of the two data sources has a spatial resolution of 1 km × 1 km, which means that carbon stocks in a particular location can vary more or less in relation to their actual value. Even knowing the data limitations, they were used because they were the best data available for the analysis. It is important to note that, even though pasture lands were found to be the best choice for land conversion to cultivate sugarcane, we did not consider to what extent such a conversion could be acceptable from the point of view of the farmers and ranchers, or how such a conversion might be feasible given the governance issues.

4. Conclusions

While confirming past studies on the carbon debt caused by land use changes, this research shows that the continued deforestation of native ecosystems is not a practical alternative for the expansion of ethanol production in Brazil. This is because these areas would become large emitters of CO_2 as a result of carbon stock loss from deforestation,

which would generate an overall carbon deficit for the country.

On the other hand, pasture was considered a feasible substitute for land use change, both because of its low CO_2 emissions and the short payback time resulting from the conversion of pasture lands to sugarcane production. Degraded pastures were considered the most suitable areas for this conversion, because in addition to the higher volume of carbon that could be stored under pastures, their ready availability could potentially double the amount of land currently used for sugarcane cultivation in Brazil.

Therefore, to reduce the pressure on ecosystems and prevent new areas from being opened up for sugarcane expansion, a more sustainable agriculture in Brazil should divert new sugarcane production to existing degraded pastures. Nevertheless, attention should be paid to the indirect damage caused by this change in land use to compensate the areas "transferred" to the production of sugarcane.

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